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THE LOCAL TIME DEPENDENCE OF THE ANISOTROPIC SOLAR COSMIC RAY FLUX

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ABSTRACT

The distribution of the solar cosmic radiation flux over the earth is not uniform, but the result of complex phenomena involving the interplanetary magnetic field, the geomagnetic field and latitude and longitude of locations on the earth. The latitude effect relates to the geomagnetic shield; the longitude effect relates to local time. For anisotropic solar cosmic ray events the maximum particle flux is always along the interplanetary magnetic field direction, sometimes called the Archimedean spiral path from the sun to the earth. During an anisotropic solar cosmic ray event, the locations on the earth viewing "sunward" into the interplanetary magnetic field direction will observe the largest flux (when adjustments are made for the magnetic latitude effect). To relate this phenomena to aircraft routes, for anisotropic solar cosmic ray events that occur during "normal quiescent" conditions, the maximum solar cosmic ray flux (and corresponding solar particle radiation dose) will be observed in the dawn quadrant, ideally at about 06 hours local time. Published by Elsevier Ltd on behalf of COSPAR.

INTRODUCTION

The purpose of this paper is to illustrate a relatively obscure technical point pertaining to the distribution of high-energy solar proton radiation over the earth's atmosphere. The location of the solar activity that is the source of earth-measured solar particulate radiation is distributed predominantly on the western hemisphere of the visible solar disk (Smart and Shea, 1995). The high-energy particle flux resulting from the solar activity streams away from the sun along the interplanetary magnetic field lines. For anisotropic solar cosmic rays, the direction of the maximum particle flux is always along the interplanetary magnetic field lines connected to the acceleration region. It has been found, from earth-orbiting spacecraft measurements, that the solar particle flux from western hemisphere solar activity is usually anisotropic, the degree of the particle flux anisotropy being dependent on the interplanetary propagation conditions which are highly variable. The solar particle flux that reaches the earth must penetrate the magnetosphere, which involves complex curved trajectories through the earth's magnetic field. The solar proton flux capable of doing this is not distributed uniformly over the earth. As a result of the complex interactions with the geomagnetic field, besides the magnetic latitude effect, there are effects that are dependent on the longitude of the measurement location. This longitude effect relates to local solar time that is determined by the orientation of the observer's position with respect to the earth-sun line. For anisotropic solar cosmic ray events, the maximum flux is likely to be observed in the local dawn quadrant as will be explained in the following sections.

ILLUSTRATION OF THE LOCAL TIME EFFECT

There is a local time effect on the observed intensity of galactic cosmic radiation; however, since the anisotropy of galactic cosmic rays is small, (of the order of 1%), the local time effect is correspondingly small. However, for anisotropic solar cosmic ray events, the local time effect can be quite significant. This is illustrated by the solar cosmic ray intensity observed at two approximately antipodal cosmic ray neutron monitors at the same cosmic ray vertical cutoff rigidity located at opposite hemispheres of the earth. The Deep River, Canada cosmic

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ray neutron monitor was located about 190 km north of Ottawa at 46.10° N, 282.50° E (geomagnetic vertical cutoff of 1.14 GV). The Kerguelen Island cosmic ray neutron monitor is located at Port aux Francais (49.35° S, 70.27° E, geomagnetic cutoff 1.14 GV). Figure 1 illustrates the increases observed by these stations during the very anisotropic solar cosmic ray event of 16 February 1984. The maximum intensity observed at Deep River was approximately six times the intensity observed at Kerguelen Island.

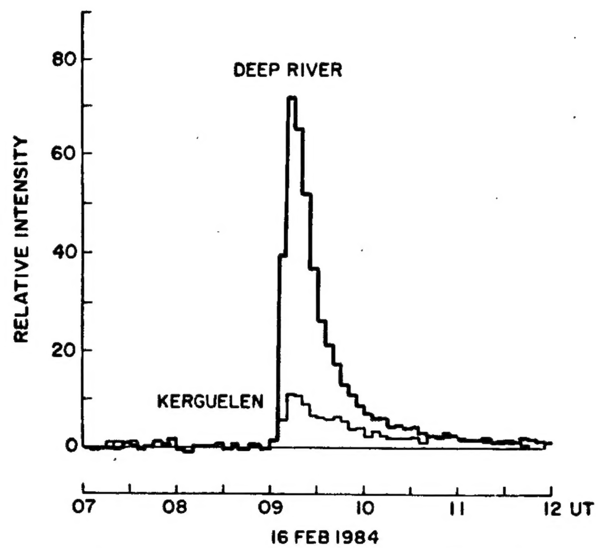

Fig. 1. Relative response of two antipodal neutron monitors, Deep River, Canada and Kerguelen Island (each having the same vertical geomagnetic cutoff rigidity) to the very anisotropic solar cosmic ray event of 16 February 1984. This event occurred at the optimum time for a maximum response at Deep River (heavy line).

Illustration of the Concept

The sun emits a highly ionized plasma (generically called the solar wind), which contains a "frozen in" magnetic field. The orientation of the magnetic field in the interplanetary medium is the interplanetary magnetic field direction. At the position of the earth in space, the average direction of the interplanetary magnetic field is about 45° west of the earth-sun line.

In Figure 2 we illustrate the spatial orientation of the sun, the earth, the earth-sun line and the simplified concept of the interplanetary magnetic field lines extending from the sun to the earth. In this figure, local time is a function of the longitude of a specific location on the earth relative to the earth-sun line. (Noon is when the sun is "overhead".) For orientation purposes consider the local time at the Greenwich meridian. When the Greenwich meridian is orientated toward the sun along the earth-sun line, it is 12 o'clock (noon) local time. Twelve hours later when the earth has rotated so that the Greenwich meridian is in a direction away from the sun, it is midnight local time. Correspondingly, when the earth has rotated so that the Greenwich meridian is perpendicular to the sun-earth line it is 18 hours local time (to the left in Figure 2) or 06 hours local time (to the right in Figure 2).

Now it is necessary to consider the effect of the earth's magnetic field on cosmic radiation. In general, the earth's magnetic field acts as a shield against cosmic radiation. The amount of shielding is a function of latitude (more properly magnetic latitude), and the technical term quantifying the amount of shielding is the geomagnetic cutoff rigidity (momentum per unit charge), which is quantified in terms of a unit called GV. The cosmic radiation is composed of energetic charged particles; a charged particle will describe a curved trajectory in a magnetic field. Consequently, the trajectory of a cosmic ray with sufficient energy to penetrate the earth's magnetic field will undergo a certain amount of "geomagnetic bending".

In the early simulations of the effects of the earth's magnetic field on cosmic ray access, Brunberg (1953) developed the concept of asymptotic directions of approach and asymptotic cones of acceptance. This concept means that only cosmic ray particles traveling from specific directions in space are allowed at specific locations on the earth. As the earth rotates throughout the day, the asymptotic cone of acceptance for each location also rotates so that the direction in space is a function of local time. Unfortunately, the determination of these asymptotic cones of acceptance (McCracken et al., 1968) is a formidable computational task. However, in this modern era of high-

speed digital computers, the cosmic ray asymptotic directions can be calculated (Shea and Smart, 1975a, 1975b) permitting a definition of the asymptotic cones of acceptance for any location. Cosmic ray specialists update these asymptotic direction calculations as the geomagnetic field evolves. In general, the maximum response direction due to the average amount of geomagnetic bending the cosmic ray trajectories undergo for mid and high latitude locations is about 45° to the east of the measurement location. There are some variations resulting from the complex interaction of the solar cosmic ray particle spectrum and the "yield" of secondary particles generated by collisions of the high-energy radiation with the nuclei of the atoms, that comprise the atmosphere, but 45° of geomagnetic bending is a reasonable approximation. Now again consider the geometry presented in Figure 2. The nominal direction of the interplanetary magnetic field is 45° west of the earth-sun line; the average geomagnetic bending is 45° to the east of a position on the earth. At 06 hours local time the asymptotic cone of acceptance is orientated toward the direction for maximum particle flux intensity of an anisotropic solar cosmic ray event.

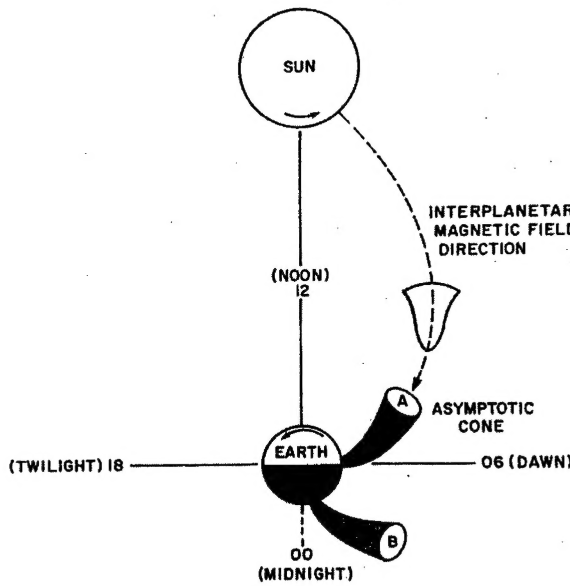

Fig. 2. Illustration of the local time effect. The earth-sun line always gives the direction of noon local time (toward the sun) and midnight local time (away from the sun). The average bending of solar cosmic ray particle trajectories through the geomagnetic field is such that the asymptotic cone of acceptance will view in the sunward direction into the nominal interplanetary magnetic field direction for a location at about 6 o'clock local time (cone A).

DISCUSSION

Now consider the data shown in Figure 1 as an illustration of the anisotropy-local time effect. The local time at Deep River, Canada (77.5° west longitude) is 5 hours earlier than GMT. Therefore, 11 hours GMT is 06 hours local time at Deep River, Canada, and as can be seen from this figure, Deep River has a larger increase than recorded at Kerguelen Island (70.27° east longitude and 16 hours local time).

We have performed calculations of the effect of a "reasonable" anisotropic solar cosmic ray flux as a function of local time and find that factors of 2 variations in the actual radiation received should be expected (Smart and Shea, 1990a). More extreme interplanetary flux anisotropies have been observed (Smart and Shea, 1990b), but they are not the usual case. During "normal" conditions, the maximum solar cosmic ray flux should be expected in the dawn quadrant (ideally at 06 hours local time) and the minimum solar cosmic ray flux should be expected in the twilight quadrant (ideally at 18 hours local time).

The 29 September 1989 Solar Cosmic Ray Event

This event has been ranked as the third largest observed since routine cosmic ray measurements began in 1936 (Smart and Shea, 1991). This event has been analyzed by a number of researchers and as a result there are models for the solar proton spectrum and the solar particle flux anisotropy (see Lovell et al., 1998).

As illustrated in Figure 3 the data acquired by the neutron monitors located near the North and South magnetic poles (Thule, Greenland and McMurdo, Antarctica) show a significant difference even though the geomagnetic cutoff at both these locations is theoretically zero. Further examination of the data acquired by high latitude neutron monitors in North America and those bordering near the North Atlantic (see Figure 4) show significant (~factor of two) differences in the magnitude of the increases recorded. All of the measurement locations used in Figures 3 and 4 have a geomagnetic cutoff that is less than the shielding provided by the mass of the atmosphere above the aircraft (the atmospheric mass cutoff), and so these differences in the observed solar cosmic ray intensity cannot be a geomagnetic cutoff effect. The largest increase is observed at Inuvik, Canada (68.35° N, 133.72° W) where the local time is about 0530 (1330 GMT – 8 hours). (It is the authors' opinion that the sudden change in the flux observed between 1300 and 1330 UT is the result of an abrupt change in the interplanetary magnetic field direction (Smart et al., 1991)).

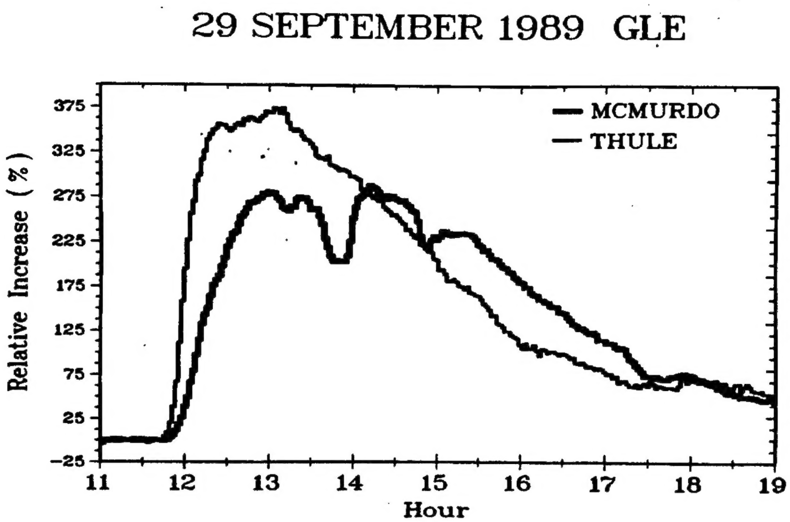

Fig. 3. Illustration of the flux anisotropy during the 29 September 1989 high-energy solar particle event as observed at the north (Thule, Greenland) and south (McMurdo, Antarctica) magnetic poles.

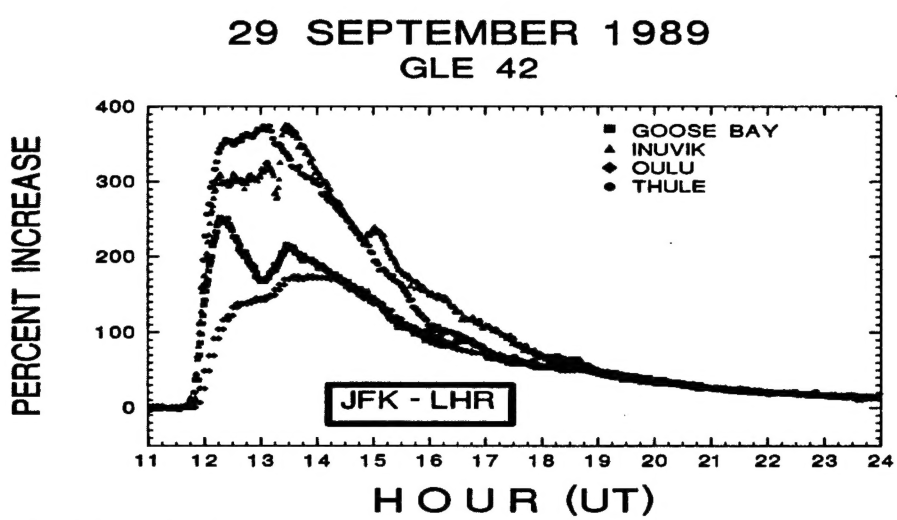

Fig. 4. The 29 September 1989 high energy solar cosmic ray event as observed by selected high latitude (low geomagnetic cutoff) neutron monitors. The variation in the magnitude of the observed increase is the result of the particle flux anisotropy. (Inuvik, 68.35° N, 133.72° W; Goose Bay, 53.27° N, 60.4° W; Thule, 76.60° N, 68.70° W, Oulu, 65.05° N, 25.47° E.) The box indicates the interval of the Concorde flight from New York (JFK) to London (LHR) on 29 September.

The Anisotropy of the 23 February 1956 Solar Cosmic Ray Event

This event has been ranked as the largest observed since routine cosmic ray measurements began in 1936 (Smart and Shea, 1991). We have recovered the existing neutron monitor data for this event. Figure 5 shows the increases observed by the cosmic ray neutron monitors (located near sea level) recording this event. In these data there are geomagnetic effects to unravel, but again a significant high-energy solar particle flux anisotropy is present. The largest increase observed by neutron monitors was at Leeds, England, (2.15 GV geomagnetic cutoff at 53.88° N, 1.58° W) while the North American neutron monitors having lower geomagnetic cutoff located west of the Greenwich meridian observed smaller increases (Ottawa, Canada, 1.08 GV cutoff rigidity at 45.44° N, 70.68° W and Chicago, USA, 1.71 GV cutoff rigidity at 41.83° N, 87.76° W). The cutoff rigidities appropriate for this epoch are from Shea and Smart (2001). In the analysis of relative event size by Smart and Shea (1991) they found that the station observing the largest increase was the station whose asymptotic cone of acceptance (see McCracken et al., 1968, Shea and Smart, 1975b) was viewing closest to the probable interplanetary magnetic field direction. The probable spectra and particle pitch angle distribution in space for this event have been derived by Smart and Shea (1990b) who found that the Leeds, England neutron monitor was viewing near to the probable interplanetary magnetic field direction while the Ottawa, Canada and the Chicago, USA neutron monitors were sampling the solar particle flux at angles about 60 degrees away from the probable maximum flux direction.

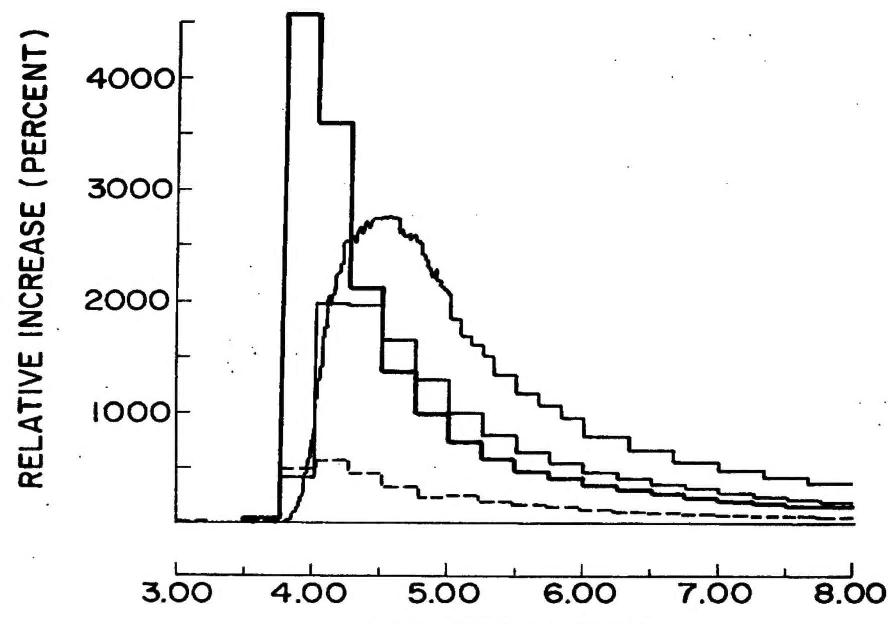

Fig. 5. Neutron monitor observations of the 23 February 1956 high-energy solar proton event. The maximum increases are: Leeds, UK (4581% as indicated by the heavy line); Ottawa; Canada (2802%); Chicago, USA (1976% as indicated by the light line); and the USS ARNEB at Wellington Harbor, NZ (575% as indicated by the dashed line).

The Effects of the Interplanetary Magnetic Field Direction

During "disturbed" geomagnetic conditions the interplanetary magnetic field directions can undergo significant deviation from the nominal direction at 45° west of the earth-sun line. In our analysis of solar cosmic ray ground level events (GLE) we have encountered extreme conditions of the observed interplanetary magnetic field direction. During the 19 October 1989 GLE, the observed direction of the interplanetary magnetic field was near the earth-sun line (Shea et al., 1991). During the 7/8 December 1982 GLE, the observed direction of the interplanetary magnetic field had a 90° westerly displacement from the "nominal position" (Smart et al., 1987). We know of no method to reliably predict what the actual interplanetary magnetic field direction will be. At the time of this publication, real time interplanetary magnetic field data are available from the ACE spacecraft.

SUMMARY

During an anisotropic solar cosmic ray event, the location on the earth having an asymptotic cone of acceptance viewing "sunward" into the interplanetary magnetic field direction will observe the largest flux (when adjustments are made for the magnetic latitude effect). To relate this to aircraft routes, any aircraft at mid or high latitude locations where the viewing direction through the geomagnetic field looks "sunward" into the interplanetary magnetic field direction will experience the highest flux during an anisotropic solar cosmic ray event. Under "nominal" conditions, that position is likely to be in the dawn quadrant (ideally at 06 hours local time). A factor of 2 variation in the solar particle flux distribution is likely to be present during the first few hours of a high-energy solar particle event.

REFERENCES

Brunberg, E.A., Experimental Determination of Electron Orbits in the Field of a Magnetic Dipole, *Tellus*, **5**, 135-156, 1953.

Lovell, J.L., M.L. Duldig, and J.E. Humble, An Extended Analysis of the September 1989 Cosmic Ray Ground Level, Enhancement, *J. Geophys. Res.*, **103**, 23,733- 23,742, 1998.

McCracken, K.G., U.R. Rao, B.C. Fowler, M.A. Shea, and D.F. Smart, Cosmic Rays (Asymptotic Directions, etc.), Chapter 14 in *Annals of the IQSY*, **1**, 198, The MIT Press, Cambridge, 1968.

Shea, M.A., and D.F. Smart, *Asymptotic Directions and Vertical Cutoff Rigidities for a Five Degree by Fifteen Degree World Grid as Calculated Using the International Geomagnetic Reference Field Model Appropriate for Epoch 1975.0*, AFCRL-TR-75-0185, 3 April 1975, Air Force Cambridge Research Laboratories, Hanscom AFB, MA, 1975a. (AD A012509)

Shea, M.A., and D.F. Smart, *Asymptotic Directions and Vertical Cutoff Rigidities for Selected Cosmic Ray Stations as Calculated Using the International Geomagnetic Reference Field Model Appropriate for Epoch 1975.0*, AFCRL-TR-75-0247, 5 May 1975, Air Force Cambridge Research Laboratories, Hanscom AFB, MA, 1975b. (AD A015736)

Shea, M.A., and D.F. Smart, Vertical Cutoff Rigidities for Cosmic Ray Stations Since 1955, *Proc. 27th Int. Cosmic Ray Conf.*, **10**, 4063-4066, 2001.

Shea, M.A., D.F. Smart, M.D. Wilson, and E.O. Flückiger, Possible Ground-Level Measurements of Solar Neutron Decay Protons During the 19 October 1989 Solar Cosmic Ray Event, *Geophys. Res. Letters*, ***18***, 829-832, 1991.

Smart, D.F., and M.A. Shea, The Concept of Using the Deep River and Kerguelen Neutron Monitors as "Flagship" Stations for Ground-Level Solar Cosmic Ray Events, *Proc. 21st Int. Cosmic Ray Conf.*, **5**, 144-147, 1990a.

Smart, D.F., and M.A. Shea, Probable Pitch Angle Distribution and Spectra of the 23 February 1956 Solar Cosmic Ray Event, *21st Int. Cosmic Ray Conf.*, **5**, 257-260, 1990b.

Smart, D.F., and M.A. Shea, A Comparison of the Magnitude of the 29 September 1989 High Energy Event with Solar Cycles 17, 18, and 19 Events, *22nd Int. Cosmic Ray Conf.*, **3**, Dublin Institute for Advanced Studies, Dublin, 101-104, 1991.

Smart, D.F., and M.A. Shea, The Heliolongitudinal Distribution of Solar Flares Associated with Solar Proton Events, *24th Int. Cosmic Ray Conf.*, **4**, 313-316, 1995.

Smart, D.F., M.A. Shea, and E.O. Flückiger, Unusual Aspects of the Ground-Level Cosmic Ray Event of 7/8 December 1982, *20th Int. Cosmic Ray Conf.*, **3**, 135-138, 1987.

Smart, D.F., M.A. Shea, Margaret D. Wilson, and L.C. Gentile, Solar Cosmic Rays on 29 September 1989; An Analysis Using the World-Wide Network of Cosmic Ray Stations, *22nd Int. Cosmic Ray Conf.*, **3**, Dublin Institute for Advanced Studies, Dublin, 97-100, 1991.

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